# A Retrospective Assessment of Partial Cutting to Reduce Spruce Beetle-Caused Mortality in the Southern Rocky Mountains

E. Matthew Hansen, José F. Negron, A. Steven Munson, and John A. Anhold

ABSTRACT

Tree susceptibility to bark beetle-caused mortality has been linked to stand characteristics such as basal area (BA) and average tree size, factors that can be manipulated through partial cutting. There is no experimental evidence, however, demonstrating the efficacy of partial cutting in spruce type. Such experiments are very difficult to complete because of the inability to manipulate bark beetle populations needed to challenge treated stands. To circumvent this difficulty, we identified spruce stands that were partially cut (for nonexperimental reasons) in advance of beetle activity and compared beetle-caused mortality to that in nearby spruce stands that were not treated. Treated stands had fewer infested stems and less infested BA than untreated stands, as well as smaller proportions of infested stems and BA. Untreated stands, however, had more residual spruce stems and BA than treated stands. Most of this difference was among stems 3–11 in. dbh with little difference in survivorship among larger stems. Spruce regeneration was not significantly different among treated and untreated stands. Spruce stand density index, spruce BA, and the number of spruce stems >11 in. dbh were the stand variables most strongly correlated with host mortality measurements. Insect population pressure appears to influence the degree of protection to residual spruce following partial cutting.

**Keywords:** Engelmann spruce, bark beetle management, *Dendroctonus rufipennis*, vegetation management, thinning

Bark beetles are natural disturbance agents of western conifer forests. Bark beetle outbreaks modify stand development and production (Schmid and Hinds 1974, Amman 1977, Romme et al. 1986), provide food and habitat for many wildlife species (Schmid and Frye 1977, Koch 1996, Martin et al. 2006), and influence nutrient and water cycling (Bethlahmy 1974, Coulson and Stark 1982, Edmonds and Eglistis 1989). Although some of these effects may be beneficial, widespread tree mortality resulting from epidemic populations often conflicts with management objectives. For example, tree mortality creates management challenges in visual corridors, recreation sites, and timber production areas.

Stand conditions have been consistently linked with bark beetle infestations in western coniferous forests (Fettig et al. 2007 and references therein). Because these attributes can be manipulated through vegetation treatments, partial cutting has been advocated to reduce potential beetle-caused host mortality (Fettig et al. 2007 and references therein). Evidence from lodgepole (McGregor et al. 1987, Amman et al. 1988) and ponderosa pine (McCambridge and Stevens 1982, Schmid and Mata 2005) systems indicates that partial cutting can significantly reduce losses to mountain pine beetles (*Dendroctonus ponderosae* Hopkins) relative to untreated stands. Experimental data are lacking for other important western conifer types, including Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) (Fettig et al. 2007). Schmid and Frye's (1976) Engelmann spruce stand hazard rating system for spruce beetle (*Dendroctonus rufipennis* Kirby; Coleoptera: Scolytidae) includes factors that can be modified by vegetation treatments such as average host diameter, basal area (BA), and the proportion of spruce in the overstory. Partial cutting in advance of bark beetle activity, also known as prevention treatment, is distinguished from sanitation/suppression treatment in that the latter is a reactive measure wherein infested and green trees are removed from an area of active beetle infestation.

It is challenging to implement robust experiments that test the efficacy of partial cutting for reducing losses to bark beetles. For example, it may take years or decades for treated stands to be exposed to bark beetle populations, and without some degree of beetle pressure, such an experiment may have inadequate results. Thus, a rigorous experimental approach is difficult to complete. Alternatively, it is possible to evaluate partial cutting as a preventive strategy by retroactively examining stands that were treated as part of forest management activities. This approach circumvents the difficulties of installing an experiment and the wait for beetles to challenge treated areas. Tradeoffs include a lack of experimental control over factors such as treatment type and their random assignment to

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi.

**Table 1. Locations of paired (treated-untreated) stands.**

| State | National Forest | District | Latitude | Longitude | No. of paired stands |
|---|---|---|---|---|---|
| Arizona | Apache-Sitgreaves | Springerville | 33.8 | −109.5 | 2 |
| Colorado | Routt | Hahn's Peak | 40.8 | −107.3 | 5 |
| Utah | Dixie | Cedar | 37.6 | −112.8 | 4 |
| Utah | Dixie | Escalante | 38.0 | −111.8 | 6 |
| Utah | Fishlake | Beaver | 38.2 | −112.4 | 2 |
| Utah | Fishlake | Fremont | 38.5 | −111.5 | 4 |
| Utah | Fishlake | Richfield | 38.6 | −112.0 | 2 |
| Utah | Uinta | Heber | 40.4 | −111.1 | 4 |
| Wyoming | Medicine-Bow | Brush Creek | 41.2 | −106.7 | 3 |

experimental units. Cognizant of these limitations, our objectives were: (1) to determine whether partial cutting reduces stand-level spruce beetle-caused mortality; (2) to compare postoutbreak stand characteristics between partially cut and unthinned stands; and (3) to examine the relationship between beetle-caused tree mortality and stand characteristics.

## Methods

Spruce mortality caused by spruce beetle increased throughout much of the central and southern Rocky Mountain states beginning about 1990 (US Forest Service 2009). We identified potential areas for evaluation from National Forests in Arizona, Utah, Wyoming, and Colorado (Table 1). We concentrated on stands treated before the current spruce beetle cycle but with treatment dates no earlier than 1970. Various types of partial cutting treatments were considered. Most treated stands were cut to BA limits, but other cutting regimes, such as patch-cuts, were also represented. From this pool of potential stands, we randomly selected a subset and established 10-ac (4-ha) square plots, a plot size suitable to estimate beetle caused mortality at a stand scale. In addition, this ensured that treated areas were at least as large; relatively small treatment blocks may be less likely to result in measurable protection against beetle infestation because bark beetle-caused mortality is influenced by small scale variations across the stand (Olsen et al. 1996, Negron et al. 2001). Aerial Detection Survey maps prepared by the US Forest Service Forest Health Protection staff were used to identify areas with nearby spruce beetle activity. Stands lacking detectable spruce beetle activity within 3 km were not considered for evaluation.

For each treated stand selected, untreated stands within a 2-km radius were identified, and one was randomly selected from that pool in effort to maximize the likelihood that treated and untreated stands had similar beetle population sizes. Our sampling protocol measured and compared populations of treated and untreated stands that shared geography and spruce beetle pressure but not necessarily stand structure or other variables. All areas sampled were predominantly Engelmann spruce except for the stands in Arizona, which had both Engelmann and blue spruce (*Picea pungens* Engelmann). All measurements were conducted during the summer of 2006 except for stands on the Routt National Forest, which were measured during the summer of 2007.

Stand characteristics were estimated by measuring nine 1/20-ac (1/50-ha) fixed-radius plots on a grid spaced at 4-chain (80.5-m) intervals. For all live and recently killed stems >3 in. (7.6 cm) dbh, we recorded species, dbh, and status (live, beetle-killed, other mortality). Live stems <3 in. dbh but greater than 6 in. (15.2 cm) tall were tallied by species in 1-in. diameter classes on a 1/300-ac (1/750-ha) fixed-radius subplot. To assess site quality, necessary for calculating the Schmid and Frye (1976) hazard rating, age at breast height and total height were measured from three dominant trees per stand and site index was estimated using curves for Engelmann spruce (Alexander 1967). Quantifying beetle-killed trees can be a problematic sampling issue, particularly when they occur in low densities or clumps. Therefore, we conducted a 100% cruise of all spruce trees within the 10-ac block. Bark beetle-killed trees were determined by the presence of spruce beetle galleries, and each was measured for diameter. In addition, year of infestation was estimated using guidelines based on our experience working in beetle-infested spruce stands:

- ≤5 years old: bark tight, fine branches persistent, possibly retaining needles;
- 6–10 years old: >90% bark retention, >50% medium (~1 cm) branches persistent;
- 11–15 years old: bark retention variable, <50% medium branches persistent.

Although our study stands were treated within the last 30 years, beetle-killed spruce snags judged to be older than 15 years dead (i.e., lacking medium branches or little bark retention) were not tallied. This prevented analyses of trees killed before treatments were applied. For stands treated before about 1990, we acknowledge the possibility of excluding trees beetle-killed *after* treatment but consider this an acceptable trade-off given the relative lack of spruce beetle activity from 1970 to 1990.

Depending on the variables examined, analyses were conducted using data from the fixed-radius plots, 100% cruises, or a combination. Generalized linear mixed models (PROC GLIMMIX, SAS Institute, Inc., Cary, NC; Littell et al. 1996) were used to detect differences among the treatments (i.e., treated or untreated). District, replicate (stand pair) within district, district by treatment, and replicate within district by treatment were included as random variables, accounting for district-to-district variance in beetle pressure. Mortality was expressed as numbers of stems and BA killed, as well as proportions thereof. When the response variable was stem count or BA, we specified a Poisson or negative binomial error distribution (a post priori decision based on residuals), whereas a binomial error distribution was specified for proportional data. Denominator degrees of freedom were specified as Kenward-Roger type. Ratios of generalized chi-square to degrees of freedom were used to check for overdispersion. In addition, model residuals were tested for spatial dependence using the Moran's I test (spdep package, R statistical software; Bivand 2002).

In separate analyses, preoutbreak stand attributes were tested as explanatory variables for the occurrence of tree mortality by recoding killed trees as live, although no adjustments were made for diameter increment. These analyses used only the fixed-radius plot data and did not explicitly consider the effect of treatment. Because generalized linear mixed models are not appropriate for comparing models (i.e., stand attributes), least squares regressions were used to obtain correlation coefficients describing model fit. These linear models, however, cannot account for the district-to-district variability in the degree of tree mortality. Therefore, in an effort to reduce this source of variance, each district mean was subtracted from observed response and explanatory variables before fitting models. Forward and backward stepwise selections were used to identify possible multivariable models.

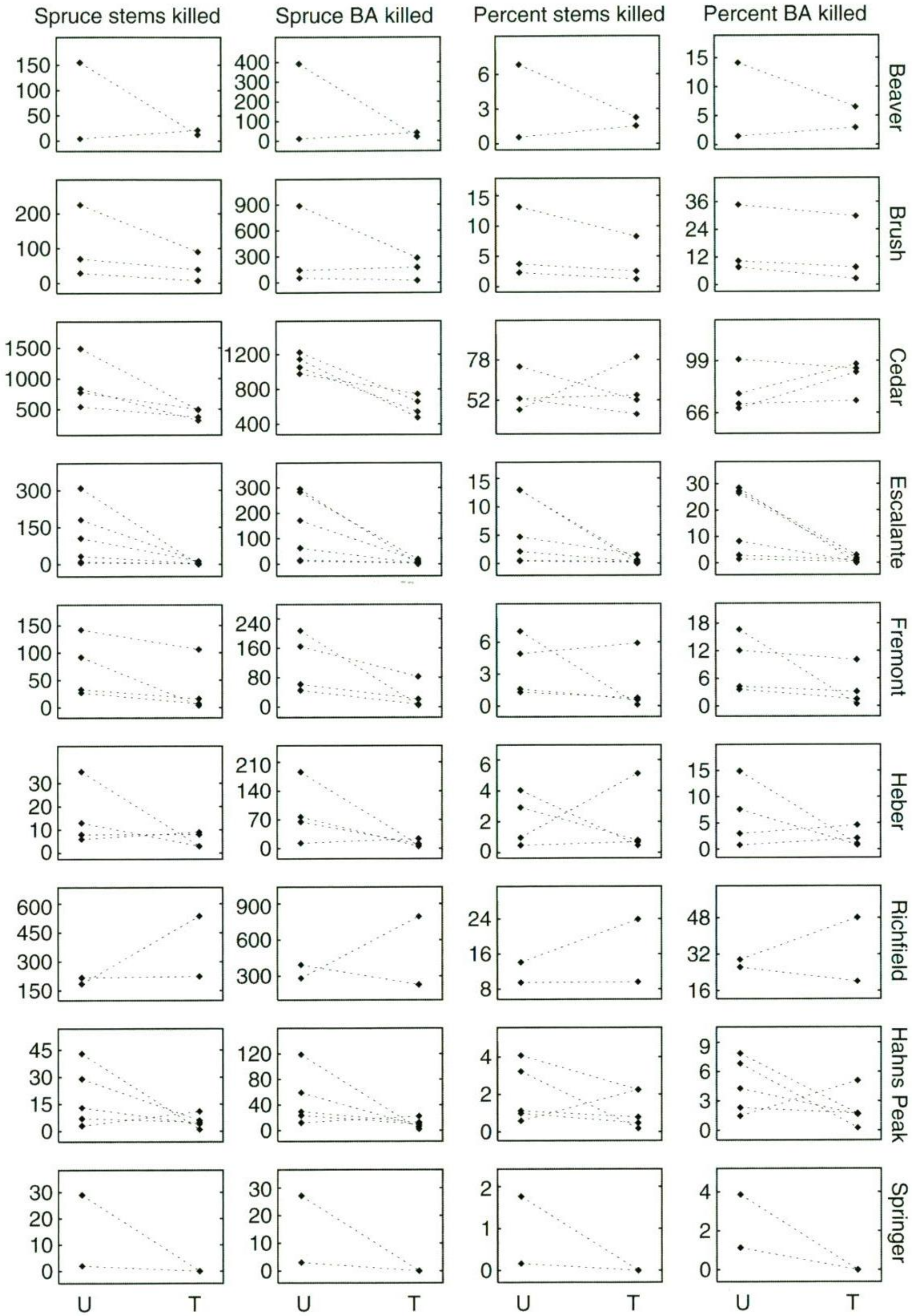


**Figure 1.** Spruce beetle-caused spruce mortality expressed as stems and basal area (BA) killed in 10-ac blocks, by district, as well as proportions thereof, for untreated (U) and treated (T) stands as measured by 100% cruise plots. The dotted lines indicate treated/untreated stand pairs, matched by proximity. Note that the pairs were not explicitly compared; instead, replicate within district was specified as a random variable in generalized linear mixed models (see Methods).

## Results

For the 100% cruise data, treated stands had fewer killed stems ($F_{1,7.417} = 13.97$; $P = 0.0066$; Figure 1) and less killed BA ($F_{1,7.345} = 17.90$; $P = 0.0035$; Figure 1) than untreated stands. Expressed as proportions killed from available preoutbreak totals, wherein the available pool was estimated from the fixed-radius plot data, treated

Table 2. **Relative fit, in adjusted correlation coefficients, of stand character variables in explaining various measures of spruce beetle-caused spruce mortality (variables are listed in approximate order of overall fit; the response and explanatory variables were adjusted by subtracting District mean values from each observation; see Methods).**

| Variable | Mortality measurement | | | |
|---|---|---|---|---|
| | Stems | BA[a] | Stems | BA |
| | | | . . . . .(%) . . . . . | |
| Spruce SDI | 0.2279 | 0.5194 | 0.2743 | 0.3713 |
| Spruce BA | 0.1803 | 0.5381 | 0.2595 | 0.3780 |
| Spruce stems >11 in. | 0.2422 | 0.4326 | 0.2453 | 0.2701 |
| Spruce stems >3 in. | 0.2237 | 0.1805 | 0.1185 | 0.1620 |
| BA (all species) | 0.0955 | 0.2814 | 0.1199 | 0.1200 |
| SDI (all species) | 0.1037 | 0.2075 | 0.1030 | 0.0742 |
| Partial hazard rating | 0.0417 | 0.1533 | 0.109 | 0.1773 |
| Site index (spruce) | NS | 0.1045 | NS | NS |
| Proportion spruce in canopy | NS | 0.0772 | 0.0677 | 0.1438 |
| Spruce quadratic mean diameter | NS | 0.0885 | NS | NS |
| Schmid and Frye hazard rating[b] | NS | 0.09 | 0.0647 | 0.1007 |
| Average dbh spruce (>10 in.) | NS | 0.0649 | NS | 0.0456 |
| Stems >3 in. (all species) | 0.0538 | NS | NS | NS |

[a] BA, basal area; NS, not significant at $\alpha = 0.05$; SDI, stand density index.
[b] The Schmid and Frye (1976) hazard rating is based on other variables in this list: BA (all species), proportion of spruce in canopy, site index, and average dbh of spruce (>10 in.). The partial hazard rating variable eliminates site index.

stands also had smaller proportions of killed trees ($F_{1,8.733} = 5.76$; $P = 0.0407$; Figure 1) and BA killed ($F_{1,8.642} = 6.97$; $P = 0.0279$; Figure 1) compared with untreated stands.

For the fixed-radius plot data, treated stands also had fewer killed stems ($F_{1,6.695} = 10.21$; $P = 0.0161$) and less killed BA ($F_{1,7.027} = 12.89$; $P = 0.0088$) than untreated stands. Expressed as proportions killed, results were also similar to those from the 100% cruise data in that treated stands had smaller proportions of killed stems ($F_{1,8} = 8.83$; $P = 0.0178$) and BA ($F_{1,7.251} = 10.11$; $P = 0.0148$) relative to untreated stands. Overall, spruce beetle-caused mortality was 7.3% (118 of 1,617 stems) on treated stands compared to 14.4% (311 of 2,164 stems) on untreated stands. Considering only stems >11 in. dbh, these proportions increased to 16.4% (88 of 535 stems) and 26.8% (204 of 762 stems) for treated and untreated stands, respectively.

Among the stand attributes we examined as explanatory variables for beetle-caused mortality, spruce stand density index (SDI), spruce BA, and the number of spruce stems >11 in. dbh produced the best model fit (Table 2; Figure 2). Inclusion of multiple covariates did not improve model fit. For all significant variables, parameter estimates were positive, indicating increased mortality with increasing levels of the explanatory variable. Model fit was modest, however, even among the best models, and most stand attributes were either nonsignificant or poorly correlated with the spruce mortality metrics. In addition, our data suggest that the relationships among stand attributes and beetle-caused mortality are dependent on the degree of beetle population pressure. At the Cedar Ranger District, where beetle-caused mortality was greater than 90% (DeRose and Long 2007), for example, considerable mortality occurred at stands with relatively low levels of spruce SDI (Figure 3). Note that mortality at the Cedar Ranger District remained positively correlated to the stand attribute but with elevated mortality levels relative to stands at the other districts.

Analyses of residual stand conditions indicated that untreated stands had more live spruce stems (>3 in. dbh) than treated stands ($F_{1,50.46} = 5.75$; $P = 0.0202$; Figure 4). Live spruce BA was also higher in untreated stands, although marginally significant ($F_{1,8.191} = 5.14$; $P = 0.0523$; Figure 4). Considering only large stems, defined as >11 in. dbh, there was no significant difference between treated and untreated stands whether considering numbers of live spruce ($F_{1,8.575} = 2.61$; $P = 0.1426$; Figure 4) or BA ($F_{1,8.613} = 4.00$; $P = 0.0780$; Figure 4). To summarize the above results, untreated stands had higher mortality rates than treated stands but, because they also started with more stems, had more surviving spruce stems (Table 3). Spruce regeneration did not significantly differ between treated and untreated stands ($F_{1,23.37} = 1.81$; $P = 0.1911$; Figure 4).

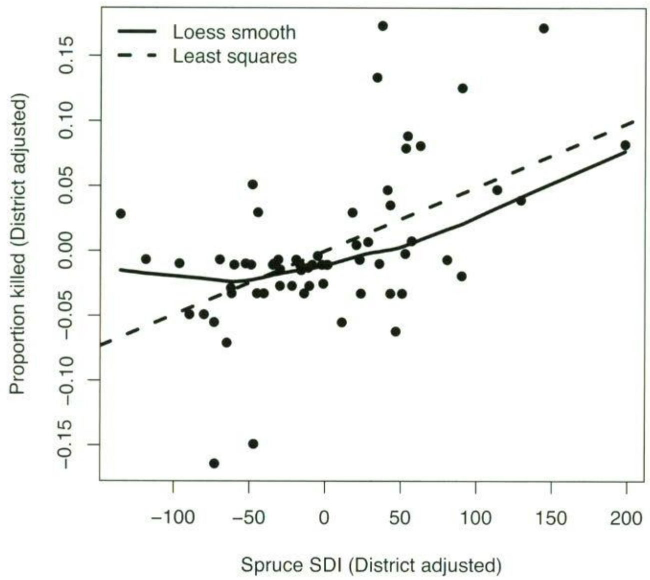


**Figure 2. Relationship between spruce stand density index (SDI) and the proportion of spruce stems killed by spruce beetles. Note that the variables are adjusted for district variances by subtracting the district-specific means from the observed values (see Methods). Relationships are similar when the explanatory variable is spruce basal area or the number of spruce stems >11 in.**

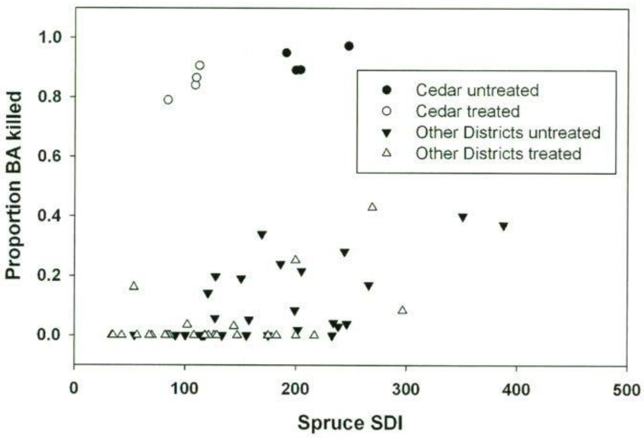


**Figure 3. Relationship between spruce stand density index (SDI) and the proportion of spruce basal area (BA) killed by spruce beetles (original scale; not district-adjusted as in Figure 2) with observations from the severely infested Cedar District shown separately. Note that these data are from the fixed-radius plots, and therefore, the proportions of spruce BA killed do not match the data shown in Figure 1.**

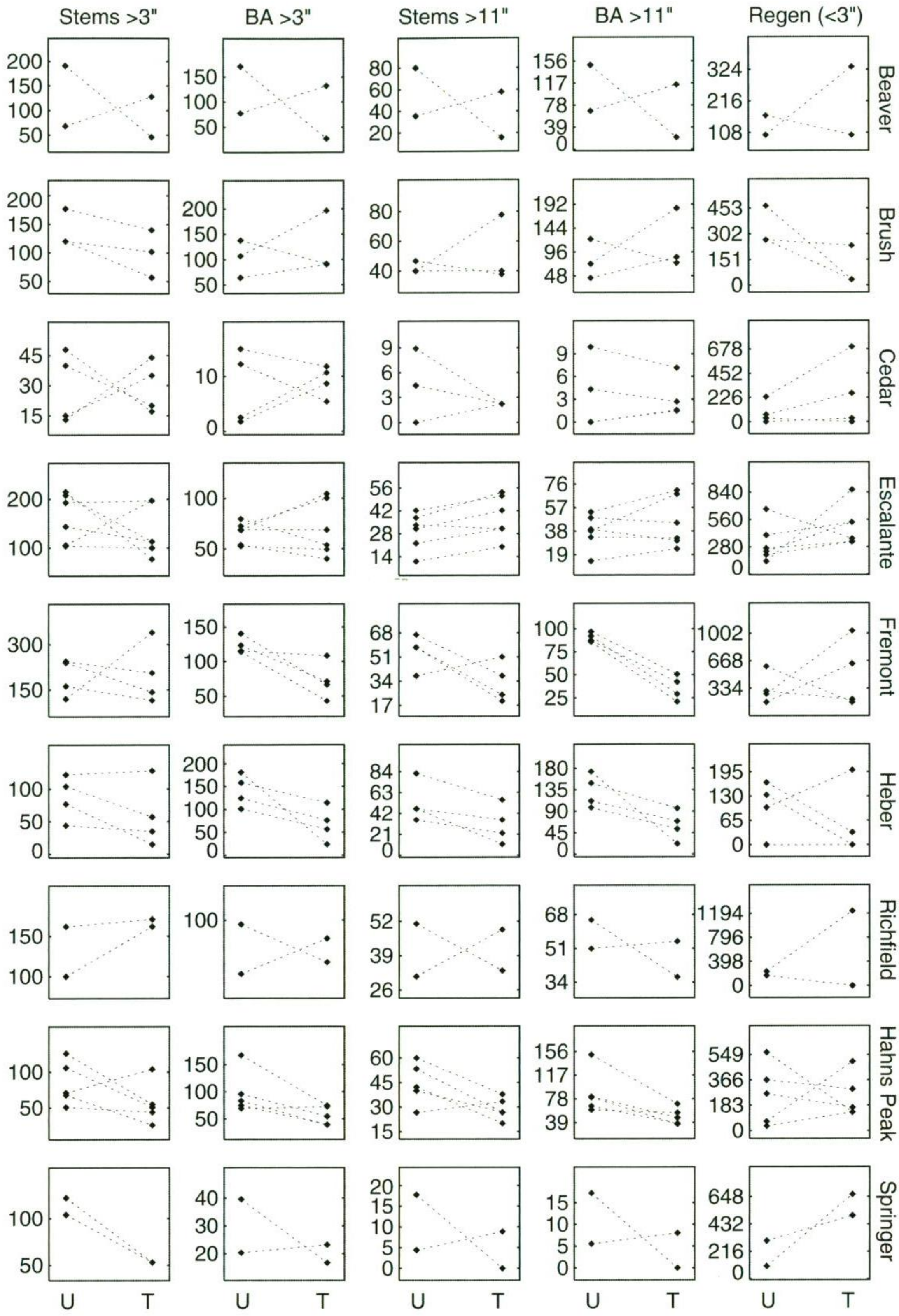


**Figure 4. Residual conditions for live Engelmann spruce among untreated (U) and treated (T) stands, expressed on a per-acre basis. The dotted lines indicate treated/untreated replicate pairs, matched by proximity. Note that the pairs were not explicitly compared; instead, replicate within district was specified as a random variable in generalized linear mixed models (see Methods). BA, basal area; regen, regeneration.**

## Discussion

Our results indicate that partial cutting in the central and southern Rocky Mountain spruce type results in significant reductions in subsequent spruce beetle-caused tree mortality, whether considering absolute spruce density and BA or the relative proportions thereof. Because treated stands had smaller pools of suitable hosts, it might

**Table 3. Summary of conditions before and after spruce beetle infestations among treated and untreated stands. Note that pre-infestation conditions among treated stands are *after* cutting.**

| Variable | Treated | Untreated |
|---|---|---|
| | .......Mean (SEM)[a]....... | |
| Preinfestation | | |
| Spruce per acre | 112.3 (75.1) | 149.6 (62.8) |
| Spruce BA (ft$^2$/ac) | 76.9 (42.3) | 120.3 (55.9) |
| Spruce quadratic mean diameter | 11.6 (2.9) | 12.2 (3.4) |
| Spruce per acre (>11 in.) | 37.2 (19.5) | 52.1 (22.1) |
| Spruce BA (>11 in.) | 60.1 (37.8) | 97.4 (57.4) |
| Spruce SDI | 123.2 (64.3) | 183.2 (72.6) |
| Postinfestation | | |
| Spruce per acre | 98.5 (70.7) | 119.5 (62.5) |
| Spruce BA (ft$^2$/ac) | 63.5 (41.6) | 86.7 (49.1) |
| Spruce quadratic mean diameter | 10.9 (3.2) | 11.0 (3.8) |
| Spruce per acre (>11 in.) | 30.0 (19.2) | 37.4 (21.3) |
| Spruce BA (>11 in.) | 46.6 (38.2) | 67.9 (47.5) |
| Spruce SDI | 102.8 (62.8) | 133.3 (69.2) |

[a] Standard error of the mean (SEM) values are simple, descriptive summaries and are not related to output from the generalized linear mixed models used in our analyses.

be expected that they would exhibit less absolute mortality than untreated stands. Thus, proportions of killed stems or BA may be more meaningful metrics of beetle-caused mortality. Note that some treated stands in our study had mortality levels similar to those at nearby untreated stands. These stands were at districts with the highest measured mortality levels (Figure 1; Cedar, Richfield, and Brush). Therefore, partial cutting appears to offer the greatest protection when beetle populations are at relatively low to moderate sizes, whereas large populations may result in widespread mortality regardless of previous treatment. Nonetheless, vegetation management that reduces, for example, spruce SDI or spruce BA should afford some protection to residual spruce (Figure 3).

Because we used a retrospective approach, our results need to be interpreted prudently. Unlike a controlled experiment, it is unlikely that pretreatment stand conditions were equivalent among treated and untreated stands. Before treatment, for example, treated stands may have had higher BA with more large-diameter spruce, conditions that made them candidates for treatment. In other words, treatments were not randomly assigned to experimental units. In addition, our approach does not include standardized treatment regimes. Our surveyed stands were treated by land managers practicing vegetation management. Most cutting was according to individual tree marking, the guidelines for which will be varied among stands, especially across a large geography (Table 1). Contrast this to controlled experiments in lodgepole pine (McGregor et al. 1987, Amman et al. 1988) wherein predetermined diameter-limit or BA cuts were replicated and compared with untreated controls. We accepted these limitations before beginning the study and acknowledge that some "optimal" cutting regime may have eluded our analyses.

In terms of residual stand conditions, untreated stands had more live spruce stems and BA, although the latter measure was marginally significant. Considering only the largest spruce (>11 in. dbh), treated and untreated stands were not significantly different for numbers of live spruce or live spruce BA. Although untreated stands had more spruce stems and greater BA relative to treated stands (preinfestation), the higher mortality rate among untreated stands resulted in near convergence of stand conditions following infestation (Table 3). Interestingly, regeneration did not differ among the treatments despite potentially improved conditions in treated stands, such as (1) some treated stands were planted; (2) mineral soil exposure during harvesting operations is favorable for Engelmann spruce establishment, whereas an undisturbed O horizon is not (Daniel 1981); and (3) seedlings in openings are more likely to become established than seedlings under canopy (Daniel 1981). For managers seeking to increase spruce regeneration while reducing spruce beetle hazard, group selection cutting may be preferable to stand-wide single-tree removal. The resulting regeneration will be highly resistant to spruce beetle attack for many decades, while the stand hazard should be reduced for the adjacent, residual trees (see Alexander 1986 and Munson 2005 for geographically specific guidelines).

Analyses of stand characteristics as explanatory variables indicate that spruce SDI, spruce BA, and the numbers of spruce >11 in. dbh are the best predictors of losses to spruce beetle. The relationships are not strong, however, and it is possible to get substantial mortality in stands with low values of these variables and, conversely, little mortality in stands with high values of these variables. Our data suggest that mortality levels are more strongly correlated to spruce beetle population size than stand characteristics, although this is confounded by the circular logic of using tree mortality levels as a surrogate for beetle population size. Also, note that we did not sample young stands (e.g., <100 years old); therefore, our conclusions only apply to older stands.

Relative to spruce SDI, spruce BA, and the numbers of spruce >11 in. dbh, the Schmid and Frye (1976) stand ratings and the variables included therein performed poorly in our analysis correlating stand characteristics to mortality (Table 2). However, the poor performance of site index as a predictor for beetle-killed mortality may reflect inappropriate use of Alexander's (1967) site index curves, which were developed from sites in Wyoming and Colorado but not Utah or Arizona, rather than lack of correlation between site quality and susceptibility to beetle-caused mortality. Although the Schmid and Frye (1976) model remains valuable for identifying susceptible stands, we believe it might be improved by considering (1) spruce SDI or spruce BA rather than *total* BA, and (2) the density of spruce stems >11 in. dbh rather than the average diameter of spruce larger than 10 in. dbh. More research, however, is needed to assign values of hazard to specific levels of these stand variables.

In conclusion, partial cutting in spruce stands appears to result in reduced losses to spruce beetle. Spruce beetle populations causing extensive host mortality, however, are likely to infest residual mature trees regardless of previous treatment. Thus, vegetation management with a goal of reducing spruce beetle-caused spruce mortality should be acknowledged as hazard reduction treatments that offer partial protection to residual trees depending on the degree of beetle population pressure. Assuming that spruce recruitment is desirable, a primary goal of vegetation management should be to maximize spruce regeneration. In this way, spruce is maintained on the landscape with stems resistant to beetle attack for future decades.

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